Computational Analysis of Added Resistance in Short Waves

Yonghwan Kim, Kyung-Kyu Yang and Min-Guk Seo

Seoul National University
Department of Naval Architecture & Ocean Engineering
Need for analysis of **added resistance in short wave** due to increase of ship length

- Investigate the effect of **different bow shape** to added resistance
State of the Art

- **Experiments**
  - Journee (1992): Wigley hull
  - Fujii and Takahashi (1975), Nakamura and Naito (1977): S175 containership
  - Kuroda et al. (2012): Different bow shapes above the waterline
  - Sadat-Hosseini et al. (2013): KVLCC2
  - Kashiwagi (2013): Modified Wigley hull, Unsteady wave analysis

- **Potential Flow**
  - Joncquez et al. (2008): Rankine panel method in time domain
  - Kashiwagi et al. (2009): Enhanced unified theory, correction in short waves
  - Kim and Kim (2011): Rankine panel method in time domain, irregular waves
  - Seo et al. (2013): Comparative study for computation methods

- **CFD – Added Resistance**
  - Orihara and Miyata (2003): RANS, FVM, overlapping grid
  - Visonneau et al., (2010): Unstructured hexahedral grid, mesh deformation
  - Sadat-Hosseini et al. (2013): RANS, overset, block structured, Level-set
**Equation of Motion**

\[ \ddot{\delta} = \ddot{\zeta}_T + \ddot{\zeta}_R \times \ddot{x} \]

\[ [M_{jk}] \{ \ddot{\zeta}_k \} = \{ F_{H.D.\,j} \} + \{ F_{F.K.\,j} \} + \{ F_{Res.\,j} \} \quad (k, j = 1, 2, \ldots, 6) \]

- \( F_{Res} \): Restoring force
- \( F_{F.K.} \): Froude-Krylov force
- \( F_{H.D.} \): Hydrodynamic force

**Linearized Boundary Value Problem**

- **Governing Equation**
  \[ \nabla^2 \phi = 0 \quad \text{in fluid domain} \]

- **Body B.C.**
  \[ \frac{\partial \phi_d}{\partial n} = \sum_{j=1}^{6} \left( \frac{\partial \zeta_j}{\partial t} n_j + \zeta_j m_j \right) - \frac{\partial \phi_I}{\partial n} \quad \text{on } S_B \]

- **Kinematic F.S.B.C.**
  \[ \frac{\partial \zeta_d}{\partial t} - (\ddot{U} - \nabla \Phi) \cdot \nabla \zeta_d = \frac{\partial^2 \Phi}{\partial z^2} \zeta_d + \frac{\partial \phi_d}{\partial z} + (\ddot{U} - \nabla \Phi) \cdot \nabla \zeta_I \quad \text{on } z = 0 \]

- **Dynamic F.S.B.C.**
  \[ \frac{\partial \phi_d}{\partial t} - (\ddot{U} - \nabla \Phi) \cdot \nabla \phi_d = -\frac{\partial \Phi}{\partial t} - g \zeta_d + \left[ \ddot{U} \cdot \nabla \Phi - \frac{1}{2} \nabla \Phi \cdot \nabla \Phi \right] + (\ddot{U} - \nabla \Phi) \cdot \nabla \phi_I \quad \text{on } z = 0 \]
Added Resistance (RPM)

- **Near-field Method, Direct Pressure Integration Method (Kim & Kim, 2011)**

\[
\tilde{F}_2 = \int_{\text{WL}} \frac{1}{2} \rho g \left( \zeta - (\xi_3 + \xi_4 y - \xi_5 x) \right)^2 \cdot \bar{n}dL - \rho \int_{\text{WL}} \left( -U \frac{\partial \Phi}{\partial x} + \frac{1}{2} \nabla \Phi \cdot \nabla \Phi \right) \left( \zeta - (\xi_3 + \xi_4 y - \xi_5 x) \right) \cdot \bar{n}_i dL
\]

\[
- \rho \int_{\text{WL}} \bar{\delta} \cdot \nabla \left( -U \frac{\partial \Phi}{\partial x} + \frac{1}{2} \nabla \Phi \cdot \nabla \Phi \right) \left( \zeta - (\xi_3 + \xi_4 y - \xi_5 x) \right) \cdot \bar{n}dL
\]

\[
- \rho \int_{\text{WL}} g z_0 \cdot \bar{n}_2 ds - \rho \int_{\text{WL}} \left( \frac{1}{2} \nabla \left( \phi_i + \phi_d \right) \cdot \nabla \left( \phi_i + \phi_d \right) \right) \cdot \bar{n}_i ds
\]

\[
- \rho \int_{\text{WL}} \left( g \left( \xi_3 + \xi_4 y - \xi_5 x \right) + \frac{\partial \left( \phi_i + \phi_d \right)}{\partial t} - U \frac{\partial \left( \phi_i + \phi_d \right)}{\partial x} + \nabla \Phi \cdot \nabla \left( \phi_i + \phi_d \right) \right) \cdot \bar{n}_i ds
\]

\[
- \rho \int_{\text{WL}} \bar{\delta} \cdot \nabla \left( \frac{\partial \left( \phi_i + \phi_d \right)}{\partial t} - U \frac{\partial \left( \phi_i + \phi_d \right)}{\partial t} + \nabla \Phi \cdot \nabla \left( \phi_i + \phi_d \right) \right) \cdot \bar{n}_i ds
\]

\[
- \rho \int_{\text{WL}} \left( -U \frac{\partial \Phi}{\partial x} + \frac{1}{2} \nabla \Phi \cdot \nabla \Phi \right) \cdot \bar{n}_2 ds - \rho \int_{\text{WL}} \bar{\delta} \cdot \nabla \left( -U \frac{\partial \Phi}{\partial x} + \frac{1}{2} \nabla \Phi \cdot \nabla \Phi \right) \cdot \bar{n}_i ds
\]

\[
\bar{n}_1 = \bar{\xi}_R \times \bar{n}, \quad \bar{n}_2 = H \bar{n} \quad H = \frac{1}{2} \begin{bmatrix}
-(\xi_5^2 + \xi_6^2) & 0 & 0 \\
2\xi_4\xi_5 & -(\xi_4^2 + \xi_6^2) & 0 \\
2\xi_4\xi_6 & 2\xi_5\xi_6 & -(\xi_4^2 + \xi_5^2)
\end{bmatrix}
\]
Cartesian-Grid Method

- **Fluid Flow Solver**
  - FVM + Fractional step
  - MC limiter
  - Cartesian grid
  - Free surface capturing (THINC / WLIC)

- **Solid Body Treatment**
  - Triangular surface mesh → Volume fraction
  - Level-set + Angle weighted pseudo-normal
  - Immersed boundary method

\[
\frac{u^n - u^n}{\Delta t} + \int_\Gamma u^n (u^n \cdot n) dS = 0
\]

\[
\frac{u^{**} - u^n}{\Delta t} = \frac{1}{\rho^{n+1}} \int_\Omega f_j dV
\]

\[
\frac{u^{n+1} - u^{**}}{\Delta t} = -\frac{1}{\rho^{n+1}} \int_\Gamma p^{n+1} n dS
\]

\[
\nabla \left( -\frac{1}{\rho^{n+1}} \int_\Gamma p^{n+1} n dS \right) = \frac{1}{\Delta t} \int_\Gamma u^{**} \cdot n dS
\]

\[
\Psi (r) = \max \left[ 0, \min \left( 2r, \frac{r+1}{2}, 2 \right) \right]
\]

\[
r = (\partial q / \partial x)_{l+1/2} f (\partial q / \partial x)_{l-1/2}
\]

\[
\frac{\partial \phi_i}{\partial t} + u \cdot \nabla \phi_i = 0
\]

\[
F_i (x) = \frac{\alpha}{2} \left( 1 + \gamma \tanh \left[ \beta \left( \frac{x - x_{l-1/2}}{\Delta x_i} \right) - \delta \right] \right)
\]
Added Resistance (CFD)

<Wigley III, $F_n=0.3$>

$R_{\text{wave}}$  
$R_{\text{calm}}$  
$R_{\text{added}}$
### Added Resistance in Short Wave

**Faltinsen et al. (1980)**

\[
\overline{F}_2 = \int_L \left\{ \frac{1}{2} \rho g \zeta_i^2 \left[ \sin^2(\theta - \beta) + \frac{2\omega U}{g} \left[ 1 + \cos \theta \cos(\theta - \beta) \right] \right] \right\} \bar{n}dL
\]

- \( n_1 = \sin \theta \)
- \( n_2 = \cos \theta \)
- \( n_6 = x_0 \cos \theta - y_0 \sin \theta \)

**Fujii & Takahashi (1975), NMRI’s method (Tsujimoto et al. (2008), Kuroda et al. (2008))**

\[
\overline{F}_2 = \alpha_d (1 + \alpha_U) \left[ \frac{1}{2} \rho g \zeta_i^2 BB_f(\beta) \right]
\]

\[
B_f(\beta) = \frac{1}{B} \left[ \int_I \sin^2(\theta - \beta) \sin \theta dl + \int_I \sin^2(\theta + \beta) \sin \theta dl \right]
\]

**Fujii & Takahashi (1975)**

\[
\alpha_d = \frac{\pi^2 I_1^2(kd)}{\pi^2 I_1^2(kd) + K_1^2(kd)}
\]

\[
1 + \alpha_U = 1 + 5 \sqrt{F_n}
\]

**NMRI (Tsujimoto et al. (2008), Kuroda et al. (2008))**

\[
\alpha_d = \frac{\pi^2 I_1^2(k_e d)}{\pi^2 I_1^2(k_e d) + K_1^2(k_e d)}, \quad k_e = \frac{\omega^2}{g}
\]

\[
1 + \alpha_U = 1 + C_U F_n, \quad C_U = \max[10.0, -310B_f(\beta) + 68]
\]

- Cross-section equal to the waterplane area
- Local steady flow velocity
Simulation Conditions

<Panel Model for Rankine Panel Method>  <Grid Distribution for Cartesian Grid Method>  <Triangle Surface Meshes for S175 Containership and KVLCC2>

<table>
<thead>
<tr>
<th>Model</th>
<th>L (m)</th>
<th>B (m)</th>
<th>D (m)</th>
<th>C_B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series60</td>
<td>100.0</td>
<td>14.29</td>
<td>5.72</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>15.39</td>
<td>6.15</td>
<td>0.8</td>
</tr>
<tr>
<td>S175</td>
<td>175.0</td>
<td>25.4</td>
<td>9.5</td>
<td>0.561</td>
</tr>
<tr>
<td>KVLCC2</td>
<td>320.0</td>
<td>58.0</td>
<td>20.8</td>
<td>0.8098</td>
</tr>
</tbody>
</table>
Motion Response (S175 Containership)

<Vertical Motion Responses of S175, $F_n=0.25$>

\[
\omega(L/g)^{1/2} \leq \frac{\xi_3}{A}
\]

- Exp. ($H/\lambda=1/120$, Fonseca, 2004)
- Exp. ($H/\lambda=1/40$, Fonseca, 2004)
- Rankine panel method
- Cartesian grid method ($H/\lambda=1/40$)

\[
\omega(L/g)^{1/2} \leq \frac{\xi_3}{kA}
\]

- Exp. ($H/\lambda=1/120$, Fonseca, 2004)
- Exp. ($H/\lambda=1/40$, Fonseca, 2004)
- Rankine panel method
- Cartesian grid method ($H/\lambda=1/40$)
< Vertical Motion Responses of KVLCC2, $Fn=0.142$ >
Grid Convergence Test of Added Resistance for KVLCC2, $Fn=0.142$

Graph showing the convergence of resistance $R/\rho g A^2B^2/L$ vs $L/\Delta x$ for two different grid resolutions $\lambda/L = 0.3$ and $\lambda/L = 0.5$. The graphs display data for different grid densities, with $<L/\Delta x >$ values of 37, 59, and 95.
Spatial variation of the physical quantities in short wavelength is more severe.
< Grid Convergence Test of Added Resistance for KVLCC2, $Fn=0.142$ >
Added Resistance (1/4)

![Graph showing Added Resistance vs. \( \lambda/L \)]

- **Added Resistance of Series 60, \( C_B=0.7, \ Fn=0.222 \)**
Added Resistance (2/4)

<Added Resistance of Series 60, \( C_B = 0.8 \), \( Fn = 0.15 \) >
Added Resistance (3/4)

[Graph showingAddedResistance vs. \(\frac{\lambda}{L}\) for different methods and experiments.]

<Added Resistance of S175 Containership, \(Fn=0.2\)>
Added Resistance (4/4)

<Added Resistance of KVLCC2, Fn=0.142>
Wave Contour and Water-Plane

<S175 Containership, \( \text{Fn}=0.2 \)>

<KVLCC2, \( \text{Fn}=0.142 \)>

<T/10 intervals from \( z=0 \) plane>

<Comparison of Water-Plane Sections>
To predict the reliable added resistance, grid convergence test should be conducted because the added resistance is sensitive to the panel size or grid spacing. Especially, a ship which has blunt bow shape requires finer grid near the ship bow region.

According to grid convergence test of Rankine panel method, more panels are required in short wave condition than in long wave condition. Also, it is recommended that panels are concentrated on bow and stern because change of body shape at bow and stern is much more severe than mid-ship region.
Conclusions (2/2)

- According to results of added resistance in short wave region, all computational methods gave good results when the vessel has blunt body, while only Cartesian grid method and short wave calculation method proposed by NMRI provided good results when the vessel has slender body. This implies that nonlinear effects which are not included in potential based solver importantly influence added resistance on a slender body in short wavelength.
Thank you all very much!

Q & A